Can a simple instrument measure polarization in gamma-ray bursts?

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Abstract

The recent claim of a high degree of linear polarization in the prompt gamma-ray burst (GRB) emission of GRB 021206 might have important implications for the underlying mechanism ultimately responsible for the GRB radiation. While the claim itself remains controversial, a full characterization of the GRB polarization has become a scientific imperative. A review of past and present polarimetry missions motivates a set of guidelines for future dedicated GRB polarization experiments. It is also argued that polarization in GRBs could be measured by a relatively simple instrument using readily available technology.

Key words: gamma-ray, polarization
PACS:

1 Introduction

The nature of the prompt GRB emission remains one of the outstanding astrophysical mysteries of the past 35 years [1]. The central problem concerns the lack of a proven mechanism that can both extract energy from a collapsing GRB progenitor, and generate prime conditions for the production of relativistic outflows [2]. Three models have emerged as the leading candidates for explanation of the prompt GRB emission. In conventional hydrodynamic models, internal or external shock fronts accelerate particles that radiate high-energy photons [3,4,5,6]. In the case of electromagnetic models, the GRB progenitor loses much of its spin in the form of an electromagnetically dominated outflow that can extend all the way out to the γ-ray emission region [7]. The cannonball model relies on inverse Compton scattering of photons to GRB

energies [9]. Although various numerical simulations have been successful in reproducing the complex structure observed in GRB light curves [10,11], the observations needed to validate any of these models are still sparse.

Perhaps the greatest observational challenge for prompt emission models has been put forward by the recent claim of polarization at the $\Pi = 80 \pm 20\%$ level in observations of GRB 021206 by $RHESSI$ (Ref. [12], CB03 hereafter). While the interpretation of the data remains controversial (Ref. [13], RF03 hereafter, and Ref. [14], BC03), it is clear that a significant measurement of polarization in GRBs might provide fundamental insight into the GRB mechanism. For example, electromagnetic models could be favored if $\Pi \approx 30$–40% is established [7,8], since hydrodynamical models have difficulties generating more than 10% fractional polarization (but see Ref. [15]). Only the cannonball model with some fine tuning may accommodate fractional polarization as large as $\Pi \approx 80\%$. Any measurement of $\Pi < 20\%$ would not exclude any of the three models since for each of them depolarization effects can enter into play. Nonetheless, an upper limit in polarization would help placing stringent boundaries for the ongoing theoretical effort.

The exciting prospects of polarization measurements in the prompt GRB emission is moving research into new directions [16]. In particular, consensus is growing that a dedicated polarization experiment is an inevitable step in constraining the GRB mechanism. In this work, after a general introduction (Sec. 2), we discuss the general guidelines for any dedicated GRB polarization experiments in the future (Sec. 3); we also argue that the technology is readily available to develop a new generation of instruments that can achieve improved sensitivity and sky coverage (Sec. 4); lastly, we outline the basic design for a relatively simple experiment that meets the conditions for a significant polarization measurement (Sec. 5).

2 Compton Scattering and Polarimetry

Polarization measurements in the soft γ-ray band, 0.2-2 MeV, commonly rely on Compton polarimetry [17]. Although practical applications may be difficult to implement, the underlying physics is already in the differential cross-section for Compton scattering as given by the Klein-Nishina formula

$$\frac{d\sigma}{d\Omega} = \frac{r_0^2}{2} \left(\frac{E'}{E_0}\right)^2 \left(\frac{E'}{E_0} + \frac{E_0}{E'} - 2\sin^2\theta\cos^2\eta\right) \tag{1}$$

where r_0 is the classical radius of the electron, E_0 the energy of the incident photon, E' the energy of the scattered photon, θ the scatter angle and η is

the azimuthal angle between the direction of the **E** vector of the incident photon (i.e. its polarization) and the plane defined by the direction of the incident photon and the direction of the scattered photon (Fig. 1). Unpolarized radiation will show no dependence on η once the effect has been averaged out over many incident photons. Polarized photons, on the other hand, have a well-defined direction of the **E** vector, which implies that the scattering probability has a maximum for $\eta=90°$ and minima at $\eta=0°$ and $\eta=180°$. Thus, photons are more likely to be scattered in the plane normal to the polarization vector.
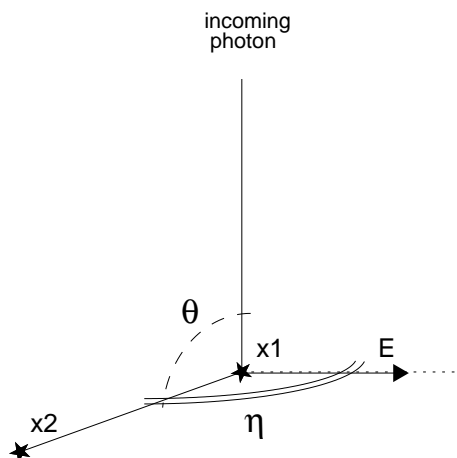

Fig. 1. Sketch of the geometry of Compton scattering, including polarization.

A Compton polarimeter is any instrument able to measure the η-modulation of Compton scattered photons; simplifying to the extreme, it only needs to record the position of the first and second interaction for each Compton scattered photon [1]. Because of the $\sin^2\theta$ factor in Eq. 1 the effect of polarization is maximum for Compton scatter angles $\theta \approx 90°$, therefore the sensitivity of any reasonable Compton polarimeter should be optimized for detecting events with such scatter angles. The dataset is given by a sample of positions $(\mathbf{x}_1, \mathbf{x}_2)$ of the first and second interaction for Compton scattered γ-rays, which we define as double interactions. If now we look at the angular distribution of the vectors $\mathbf{x}_1$-$\mathbf{x}_2$ in the plane normal to the direction of the incoming photons, given a fractional polarization Π, the signal S as a function of the angle η will show a sinusoidal modulation

$$\frac{dS}{d\eta} = \frac{S}{2\pi} \left[1 - \mu\Pi\cos(2(\eta - \phi))\right] \qquad (2)$$

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[1] En passant, the reader should notice that these requirements are only a subset of the requirements for Compton imaging, where also the energy and the correct time sequence must be determined.

where μ is the instrumental modulation factor and ϕ is the polarization angle of the incident photons [17,18].

Now assuming that B is the total number of background events (un-modulated with respect to η), the expected signal-to-noise ratio for polarization measurements σ can be written as

$$\sigma = \frac{\mu\Pi S}{\sqrt{2(S+B)}} \tag{3}$$

Therefore, the minimum detectable fractional polarization Π_{min} (at the n_σ significance level) can be shown to be

$$\Pi_{min} = n_\sigma \frac{\sqrt{2(S+B)}}{\mu S} \tag{4}$$

where the position of the source in the sky is tacitly included in the instrumental modulation factor μ.

3 Considerations for Future GRB Polarization Experiments

Our previous discussion indicates that the design requirements for future GRB polarization experiments can be summarized as: sensitivity in a suitable energy range, minimized background B, maximized signal S, and maximized μ.

Let us start with the energy range. While Compton scattering can occur at lower energies and the Compton cross-section actually has a broad maximum at about 100 keV, it is - for most materials - the dominant process in some energy band centered around $\sim$1 MeV. For example, for carbon, $Z=6$, Compton scattering is the main contribution to the total cross section between 100 keV and 10 MeV. This energy range is well-suited for GRBs since the peak energy of the GRB spectrum E_{peak} is narrowly distributed around $E_{peak} \approx 250$ keV [19].

The requirement of a low background level is actually more relaxed than in traditional MeV γ-ray observations (e.g. [20]). The fact that the prompt GRB emission needs to be integrated over a relative short interval of time, corresponding to the duration of the burst, significantly reduces the relevance of the atmospheric γ-ray background and of the background due to neutron interactions, spallation and activation. Both CB03 and RF03 show that the most dangerous source of background is the chance coincidence of two independent

events, each of them giving only one interaction, within the same time window τ that defines an event. Such an occurrence clearly fakes a genuine double event. Fortunately, the dependence of the rate of chance coincidence events r_B on the source rate r_{source} (detected rate of single events) and τ may be written as

$$r_B = r_{source}^2 \times \tau \tag{5}$$

Thus r_B may be made negligible provided a sufficiently narrow time window τ. For example, the COMPTEL instrument exploited a time-of-flight measurement to reconstruct the direction of the γ-rays, with a timing accuracy better than ~ 1 ns [21]. Conservatively assuming that each photon is individually time tagged with a accuracy of $\tau \sim 10$ ns, a source rate r_{source} as high as 10 kHz implies a negligible rate of chance coincidences $r_B \approx 1$ Hz. The fast timing requirement suggests that *scintillator counters* might be a logical choice for future GRB polarization experiments.

The signal S is defined as

$$S = F \times A_{eff} \times T$$

where F is the flux impinging of the detector in units of photons cm^{-2} s^{-1}, A_{eff} is the effective area and T is the duration of the GRB. Since F and T are intrinsic properties of the GRB, a large S can be accomplished only by increasing A_{eff}. The NaI array of BATSE Large Area Detectors (LADs) allowed for the entire sky to be viewed simultaneously with an effective area $A_{eff} \approx 2000$ cm^2 [22]. Taking BATSE as the prototypical sensitive detector for GRBs, we assume that a comparable effective area must be achieved. It should be noticed that the effective area for double interactions is only a fraction of the effective area *à la* BATSE. In fact, a γ-ray not only has to interact in the detector (through Compton scattering), but also the scattered γ-ray must re-interact and be separately detected. More details on how to achieve a large effective area are given in Sec. 4.

Finally, the modulation factor μ should be no worse than the $\mu \approx 20\%$ already achieved by $RHESSI$ (CB03), which suggests that a similar geometrical arrangement with a fixed number of cylindric detectors distributed over a planar support-structure is already advantageous.

Before proceeding further in the discussion, it is worthwhile stressing that, following approach in CB03 and RF03 and their analysis of the $RHESSI$ data, there are no specific requirements on energy resolution and source imaging capability of the polarimeter itself.

4   Basic Design of an Advanced GRB Polarimeter

Before discussing the proposed design in detail, it is convenient to review some characteristics of $RHESSI$. Although primarily designed for the study of the physics of particle acceleration in solar flares, $RHESSI$ has proven sensitive to GRB polarization measurements using its germanium focal plane detectors. Oddly enough, of the approximately 80 GRBs detected by RHESSI, detailed analysis has only yielded one seemingly plausible polarization measurement in the case of GRB 021206 (CB03). It is possible that the report of polarization in GRB 021206 has been overestimated (RF03); however, the detection of polarization only in the case of GRB 021206 is not entirely surprising given its unusual properties, i.e. a $< 1°$ localization, a fluence ranking in the top 5% among all observed GRBs [23], and the fact of being only slightly off-axis with respect to $RHESSI$.

Upon careful examination, $RHESSI$ offers several advantages over alternative polarimetry configurations. We are thus lead to consider a detector design that combines the geometrical arrangement of $RHESSI$, and an effective area comparable to BATSE as the basis for a future GRB polarimetry experiment. As the "building block" of such an instrument we consider a cylindric detector unit made of scintillator material coupled with possibly one single photodetector (e.g. a standard photomultiplier tube). This would play the same role as the $RHESSI$ Ge detectors. Like in the CB03 analysis, the interaction location corresponds to the position of the detector unit. In $RHESSI$, the distance between the centers of two neighboring detector units is about twice the diameter of the detector unit itself, and we assume the same geometry.

The main constraints on the design of the cylindric detector unit derive from the requirement of a large effective area for double interactions. Here a configuration as in Fig. 2 is assumed, and r is the radius of the cylinder and t its height. A large geometrical area πr^2 and enough "thickness" t (e.g. several mass attenuation lengths [2] so that $>90\%$ of the impinging flux will interact within the detector) are the starting point for a large effective area. Since we are interested in double interactions, we now want to maximize the number of double events interacting in two separate detector. For this reason, the radius of a detector unit should be about 1 mass attenuation length, in order to guarantee that

1. a large fraction of the Compton scattered photons does reach a second detector without being absorbed within the same detector unit;

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[2] The mass attenuation length is defined as the intensity I remaining after traversal of a thickness t (in units of mass/unit-area) of the specified material: $I = I_0 e^{-t/\lambda}$. It depends on the energy of the γ-ray. A large database is available at http://physics.nist.gov/PhysRefData.

2. once a scattered photon reaches a second detector unit, it has a large enough probability to interact.

Low Z materials would be well suited for building a large area detector unit minimizing the probability of a double interaction within the same unit. Organic scintillators (plastic or liquid, possibly loaded with high Z elements) are usually compounds or mixtures of low Z elements and they would fully meet the requirement of fast timing capability. They are also extremely cost-effective, easy to operate and easily machinable for building large area detectors, as opposed to costly Ge detectors. Their fast (ns) response makes them ideal for applications which require an excellent timing capability.

The one drawback in using low Z materials in general and organic scintillators in particular is that the mass attenuation length would be too large (10 cm or more for non-loaded organic scintillators at γ-ray energies around the Compton minimum in the cross-section, i.e. $\sim$1 MeV), which might make the size of the detector impractically large. How serious this problem is needs to be studied in greater detail, considering organic scintillators as NE 226 which has a relatively high density (1.61) and is well suited for detecting γ-rays, or NE 316, Sn loaded.

Given a $RHESSI$-like geometrical arrangement with n counters, we define the total effective area as

$$A_{eff} = n\pi r^2 \left(1 - e^{-t/\lambda}\right) \tag{6}$$

i.e. we consider an on-axis GRB. The mass attenuation length λ should be evaluated at a few hundreds keV, given the spectral properties of most GRBs, and we assume $r \approx \lambda$. To make $(1-e^{-t/\lambda}) \approx 1$, the thickness has to be $z/\lambda \geq 3$. A large thickness also increases the solid angle for scattered photons to hit a second detector, therefore improving the efficiency to Compton scattered events. For plastic or liquid scintillator counters, we may assume $r \sim 7$ cm, and as few as $n =15$ would already give a 2000 cm^2 effective area *à la* BATSE. It is easy to imagine a scaled up version, with an effective area exceeding the BATSE effective area by a factor of two or more.

Roughly, compared to $RHESSI$, an instrument as in Table 1 would have 6 times more geometrical area, but the gain in effective area *for double events* should be much larger. The background due to chance coincidence of single events would be negligible, compared to $RHESSI$ which has a time window τ=5 μs, as in RF03 [3] . For example, assuming $\mu \approx 20\%$, a gain over $RHESSI$ of a factor of 10 in effective area, $B \approx S/2$ for $RHESSI$ (as in CB03, but RF03 suggest a much larger B), and $B \ll S$ for the proposed instrument, we

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[3] The precise value of τ in CB03 is not given.

instrument	BATSE	RHESSI	this work[c]
effective area[a] [cm^2]	2000	360	2000
background[b] [Hz]	–	500	1

Table 1

Comparison between *RHESSI*, BATSE and the present work; all the figures are roughly accurate. [a]: the effective area, calculated from Eq. 6, is essentially the geometrical area. [b]: the background is defined as in Eq. 5, assuming an interaction rate of 10 kHz; for *RHESSI*, we assume τ=5 μs, as in RF03. [c]: we assume τ=10 ns and a geometrical area of 2000 cm^2, as discussed in the text.

would obtain from Eq. 4

$$(\Pi_{min})_{RHESSI} = n_\sigma \frac{\sqrt{3S}}{\mu S} = n_\sigma \frac{\sqrt{3}}{\mu \sqrt{S}} \approx 4 \ (\Pi_{min})_{this\ work}$$

i.e. a simple instrument as the one sketched in this work would be more sensitive to polarization than *RHESSI*, at a fraction of the cost.
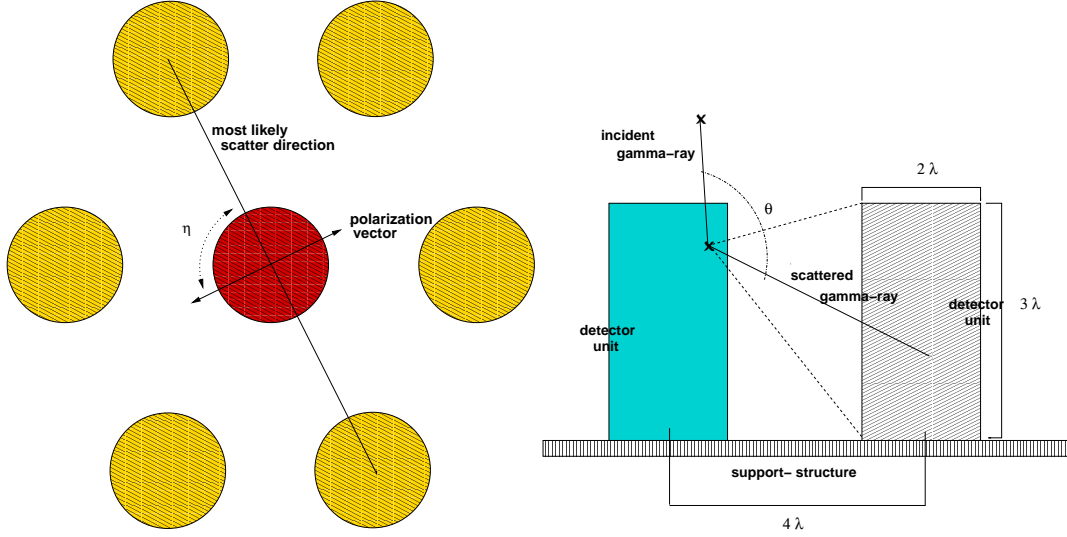

Fig. 2. Sketch of a *RHESSI*-like experimental apparatus for polarimetry measurements. *Left:* top view. *Right:* side view of two detector units; θ is the Compton scatter angle, λ is "mass attenuation length".

5 Feasibility of a Balloon Borne Experiment

A balloon payload is an attractive option to carry GRB polarization measurements because of its minimal operation cost and complexity compared to a satellite mission, and the possibility to come on line in a much shorter time. If a balloon borne experiment can achieve a field of view as large as

BATSE [4], given a comparable effective area, it would trigger as many GRBs as BATSE, i.e. about one GRB per day based on the rate of events in the BATSE 4B catalog [24]. Collecting a sample of at least ∼10 GRBs appears within reach for a long-duration balloon flight lasting for more than 20 days [5], or even through the combination of several shorter balloon flights (e.g. [26] which lasted 27 h). Whether such a sample would allow at least one significant polarization measurement in the whole GRB sample is impossible to predict without the entailing analysis of a final design. Clearly, the success of a balloon experiment will depend not only on the details of the instrument but also in the brightness and hardness of the GRB sample; GRB 021206 was an extraordinarily bright event, with a fluence of $1.6 \ 10^{-4}$ ergs cm^{-2} [23] placing it in the upper tier of the BATSE catalog [24]. Making the bold assumption that the signal S scales as the fluence, the proposed instrument should be able to return solid measurements for at least one GRB event over 20 days. An estimate may be based on the peak flux of known GRBs in units of ph cm^{-2} s^{-1}, as shown in Fig. 3 (from [24]). Eq. 4 may be turned around to give S, fixing Π_{min}=50%, n_σ=3 and $B \approx S$, with B mainly determined by the atmospheric γ-ray flux

$$S = \left(\frac{2n_\sigma}{\mu \Pi_{min}} \right)^2 = 3600 \text{ double events} \tag{7}$$

S can be written in terms of the peak flux PF as

$$S = T[\text{s}] \times PF[\text{ph cm}^{-2} \text{ s}^{-1}] \times f \times A_{eff}[\text{cm}^2] \tag{8}$$

where T is a proper integration time and $f \times A_{eff}$ is the effective area for double events (with $f < 1$ by definition). Assuming some reasonable values such as T=2 s, f=10% and A_{eff}=2000 cm^2, a peak flux of ∼10 ph cm^{-2} s^{-1} would allow to test $\Pi_{min} > 50\%$ at the 3σ level. From Fig. 3 it looks perfectly plausible that polarization should be detectable in about 10% of the triggered GRBs.

An additional requirement for a successful polarimetry experiment rests on its ability to determine the GRB localization. It is important to stress that,

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[4] One should take care that the field of view is large not only for triggering a GRB but also for measuring polarization, a rather demanding requirement. For example, a cubic instrument with five sides similar to the configuration proposed here may come close to solving the problem

[5] Launched from Antarctica, the HIREGS balloon borne experiment [25] lasted more than 20 days. Balloon flights over Antarctica are troublesome because of a high background level in the MeV, but may be compatible with the loose background requirement of the present work.
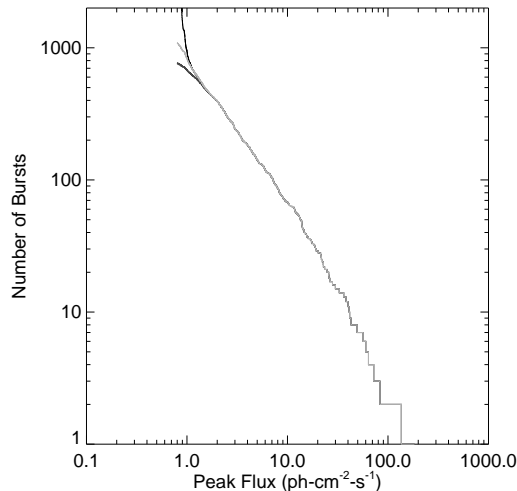
Fig. 3. An example of log$N$-log$P$ integral distribution for GRBs in the BATSE 4B catalog (from [24]).

while the source position is usually well known a priori in polarization measurements, it is not the case for GRBs. The GRB position in the sky should be known in order to define the azimuthal distribution and modulation of Compton scattered photons. It also enters the analysis in ruling out possible asymmetries that may mimic polarization. A detailed analysis indicates that a relatively coarse localization should suffice. Such a localization can be achieved by the instrument itself, improving over BATSE. Alternatively, a combination of already existing instruments (HETE, IPN) and the upcoming SWIFT and GLAST missions may provide enough sensitivity for an independent localization of the GRB. A successful polarization experiment must also be able to properly account for systematic uncertainties such as asymmetries in the mass distribution of the instrument. This can be accomplished either by careful Monte Carlo simulations, or alternatively by rotation of the detector, as for $RHESSI$ [16]. Details on this notoriously delicate issue will require a careful analysis in the future.

An alternative to a balloon borne experiment is to exploit a future satellite mission where a polarization instrument might "piggyback" another instrument, possibly with imaging capability in soft γ-rays, which would significantly increase the exposure and offer a good localization capability. Notwithstanding, a balloon phase is vital to provide proof of concept for an instrument with an effective area comparable to BATSE.

6   Conclusions and Future Prospects

The next generation of proposed instruments with the capability of measuring polarization in soft γ-rays, including ACT [27,28], GRAPE [16], and the design discussed here, promise important constraints of the prompt GRB emission mechanism. While the ACT and GRAPE proposals have a much broader scope than just measuring GRB polarization, the concept put forward in this work is the one of an instrument which will just measure GRB polarization. Even an upper limit on polarization will impose stringent limits for different GRB models. Polarization measurements might also provide a novel way to explore the mechanism responsible for the hard, short class of GRB events since the instrumental resolution is not limited to long events. In particular, it is important to explore if there is more than one class of GRBs in terms of polarization. To assess the potential of a future experiment requires a full-fledged Monte Carlo simulations including a detector mass model, GRB flux distribution and a proper background model. This is of vital importance when evaluating the need for rotation of the detector and modeling the sensitivity of large area experiments. The estimates given in this work are based on simple experimental arguments, scaling the performance of proven instruments like $RHESSI$ and BATSE, and should be useful in setting the initial guidelines for new experimental approaches to GRB polarization measurements. Summarizing, the minimal requirements in our analysis are:

1. an effective area of 2000 cm^2 for "triggering" GRBs;
2. enough sensitivity to a large fractional polarization for GRBs with peak flux of $\sim$10 ph cm^{-2} s^{-1}.

There is at least one last point that has been overlooked in most of the current polarization literature including this work, which is the possibility of energy measurements. Given a fully contained double event, Compton kinematics must be obeyed and this constraint should improve background rejection. In principle, it might even be possible to apply Compton imaging techniques [21] to image the GRB, as would be the case (at a very refined level) for the proposed ACT. Lastly, we have pointed out that the technology to take the next step in polarimetry experiments is readily available and a working instrument may be built in relatively short time. The simplicity of the proposed instrument derives from the fact that its goal is narrowly focused on a single, well-defined measurement without stringent requirements on energy resolution, source imaging capability and low background level. Alas, a simple instrument does not imply a simple experiment.

Acknowledgments

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